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Toward a Measurement of the W Boson Mass with the D0 Detector

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Outline

1. Motivation
2. Overview of Method
3. Strategy for the Measurement
4. Details of the Analysis
5. Systematic Uncertainties
6. Prospects and Conclusion

The W Boson

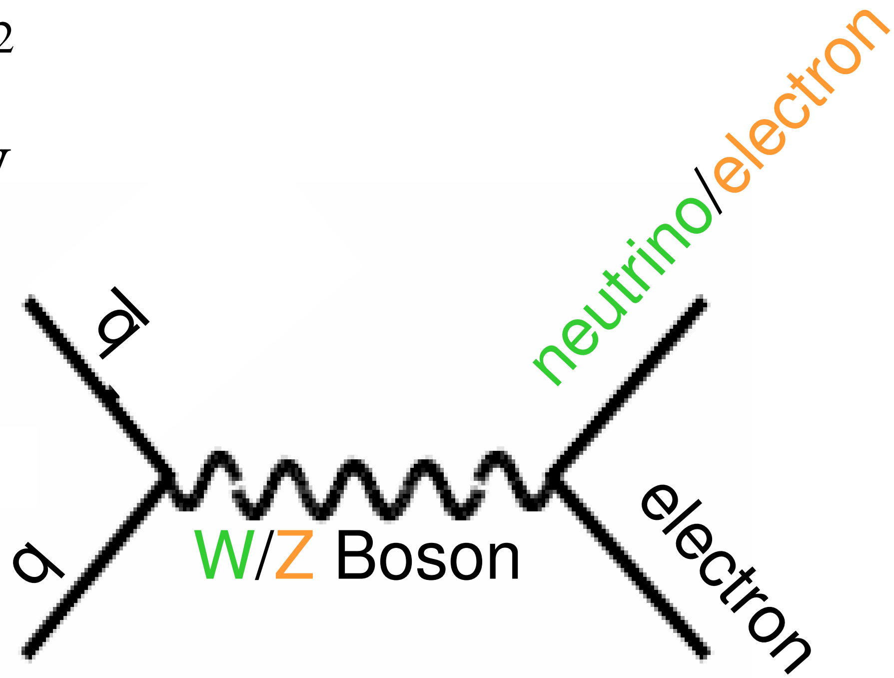
- In the Standard Model the electroweak sector is described by three well-measured parameters:

$$\alpha_{EM}(m_Z)^{-1} = 127.904 \pm 0.019$$

$$G_F = 1.6637(1) \times 10^{-5} \quad \text{GeV}^{-2}$$

$$M_Z = 91.1876(21) \quad \text{GeV}$$

- At tree level these parameter are related by:



$$M_W = M_Z \cos\theta_W$$

$$M_W^2 = \frac{\pi\alpha}{\sqrt{2}G_F \sin^2(\theta_W)}$$

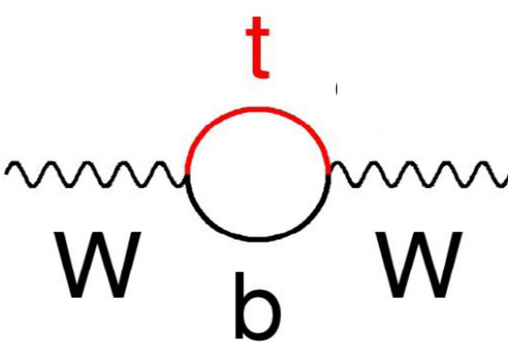
$$M_Z^2 = \frac{\pi\alpha}{\sqrt{2}G_F \sin^2(\theta_W)\cos^2(\theta_W)}$$

Motivation

- Beyond tree level we start to test the SM.

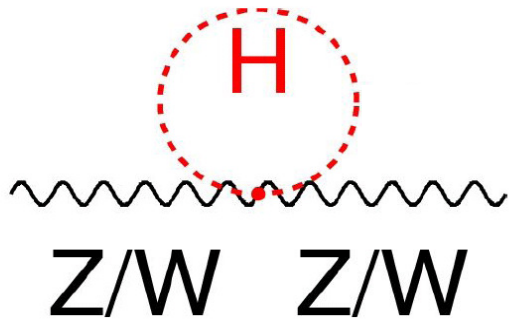
- Change in M_W is described by factor ρ:

$$M_W = \frac{M_{W,tree}}{\sqrt{1-\rho}}$$



Heavy quark loop

$$\rho \sim M_{top}^2$$



Higgs coupling

$$\rho \sim \ln M_H$$

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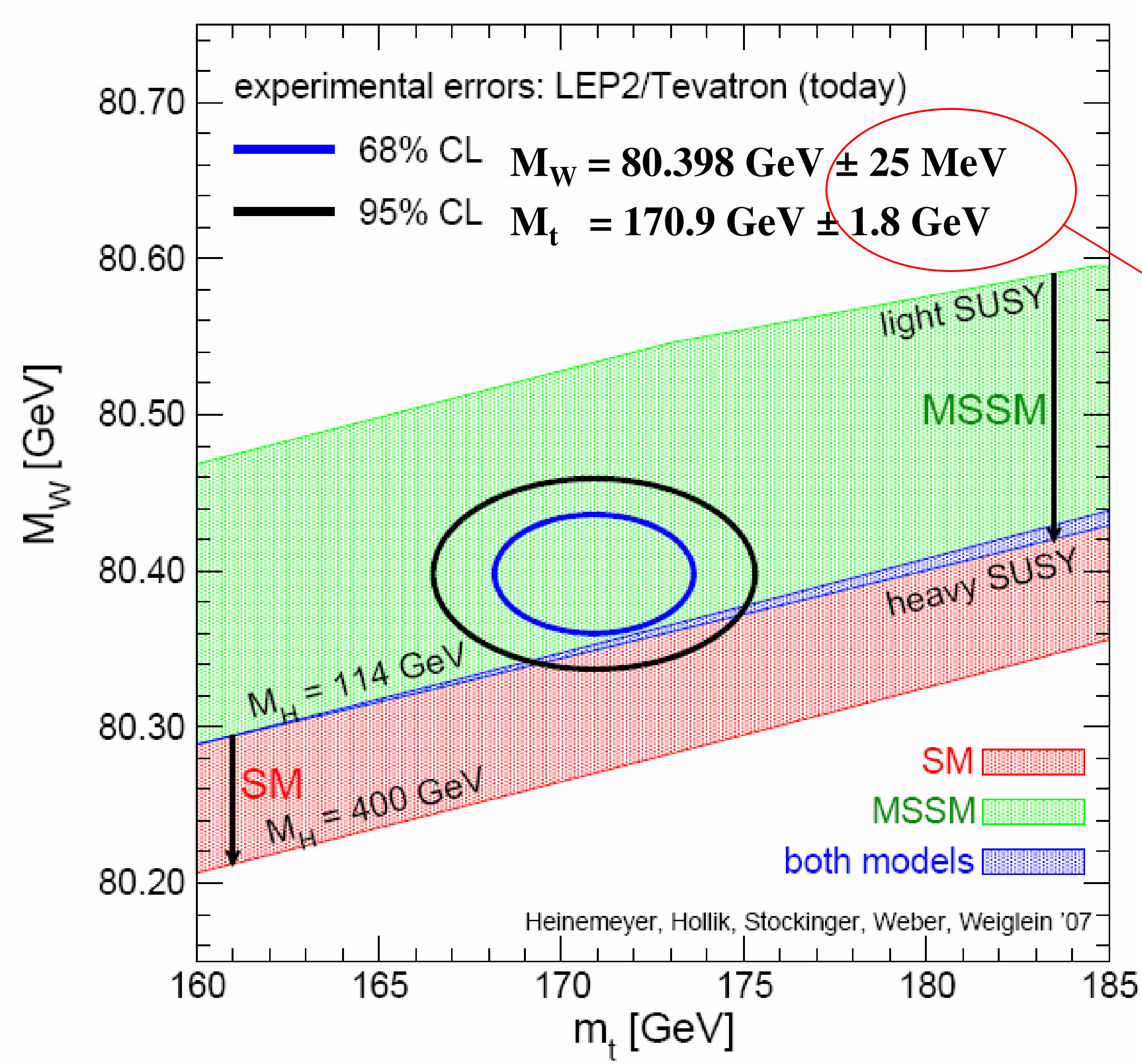
Motivation



S. Heinemeyer, W. Hollik, D. Stockinger, A.M. Weber, G. Weiglein '06
http://quark.phy.bnl.gov/~heinemey/uni/plots/

Precise measurements of W and top masses constrain the Higgs mass.

ΔM_{top} = 1.8 GeV

Corresponds to:

ΔM_W = 10 MeV

Improvement in M_W is needed.

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Previous Measurements

D0 Run II Goal:
- With 1/fb
- Electron channel

ΔM_W < 50 MeV uncertainty

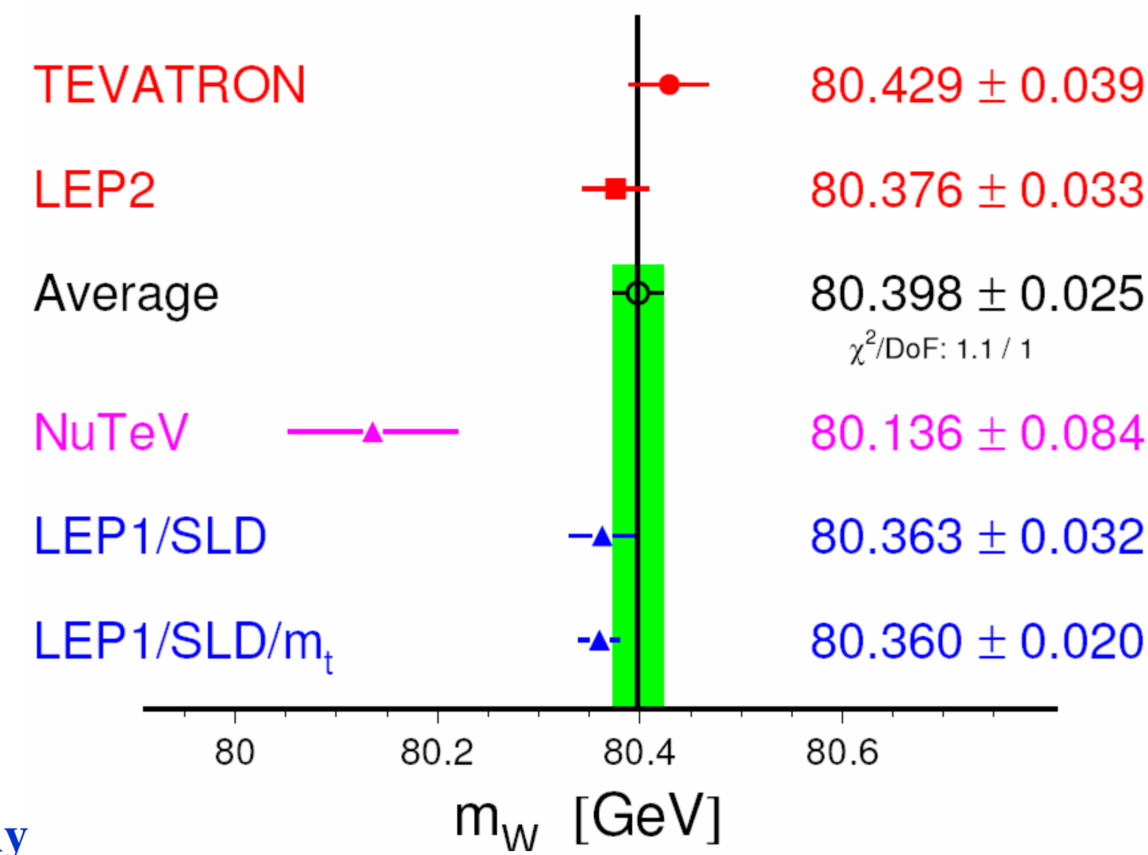
~1 part in 10,000

D0 Run 1: 84 MeV (100/pb)

Dominant systematic uncertainty is Calorimeter Energy Scale ➔

Run I EM scale known to 0.08% =>
ΔM_W = 70 MeV
(For 50 GeV electron, 0.08% is only 40 MeV)

Run I hadronic recoil known to 1% =>
ΔM_W = 40 MeV
(For 5 GeV recoil system, 1% is only 50 MeV)



arXiv:hep-ex/0612034v2
Updated for 2007 at
http://www.cern.ch/LEPEWWG

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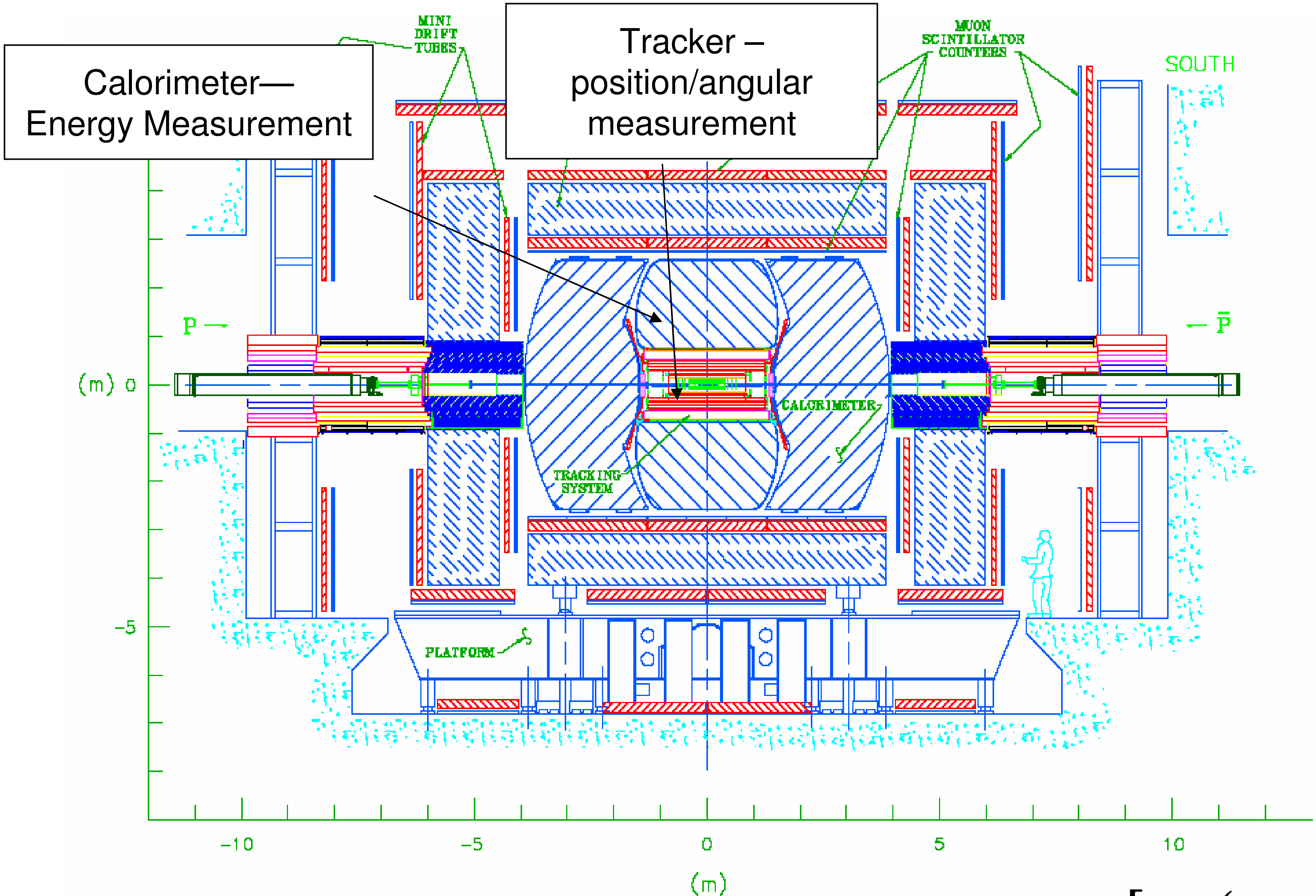
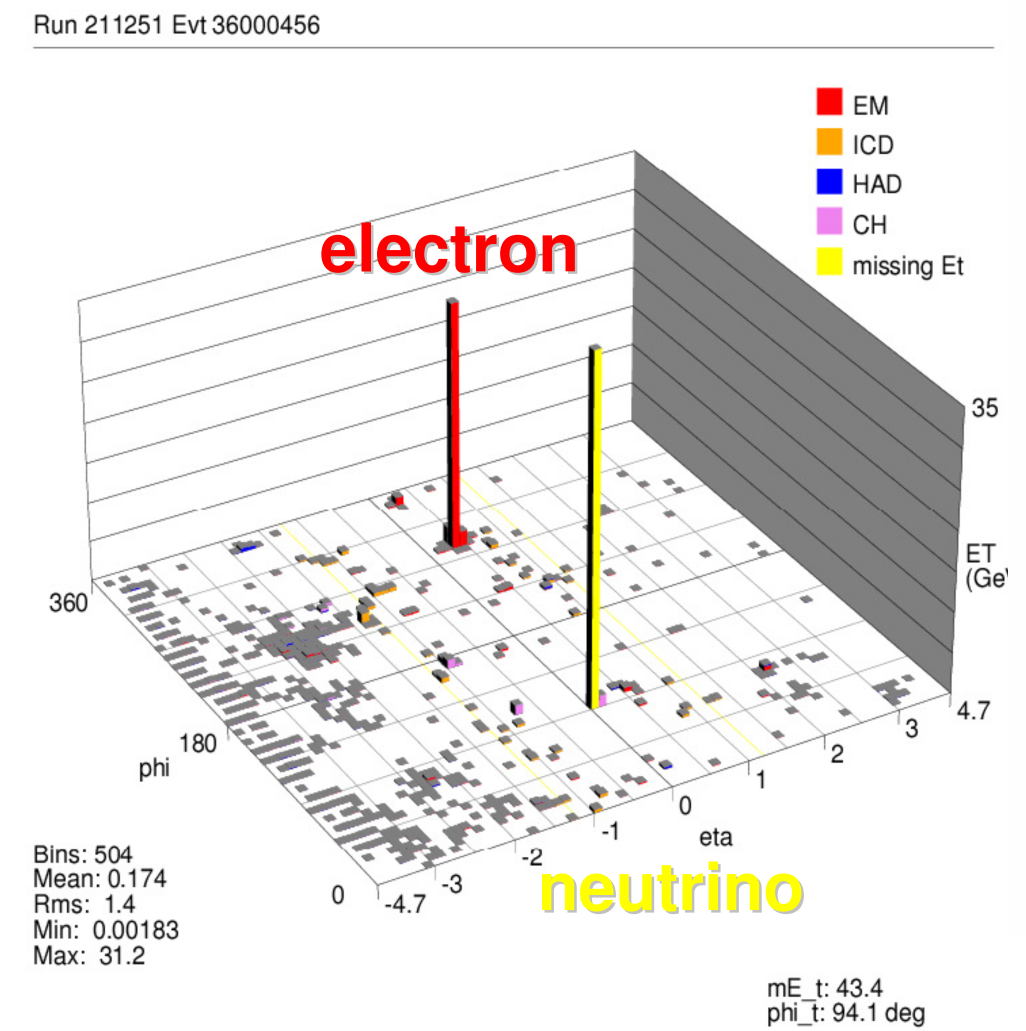
D0 Detector – Run II



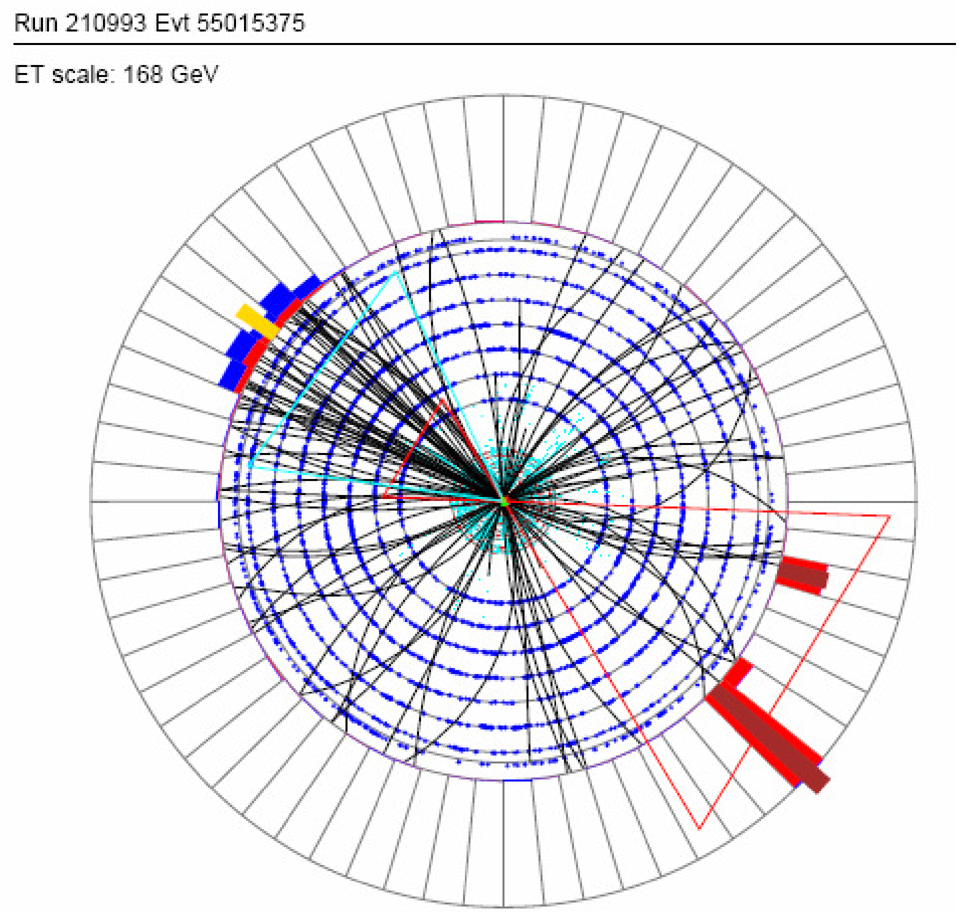
$$\eta = -\ln\left[\tan\left(\theta/2\right)\right]$$

Event Display

W->eν in data

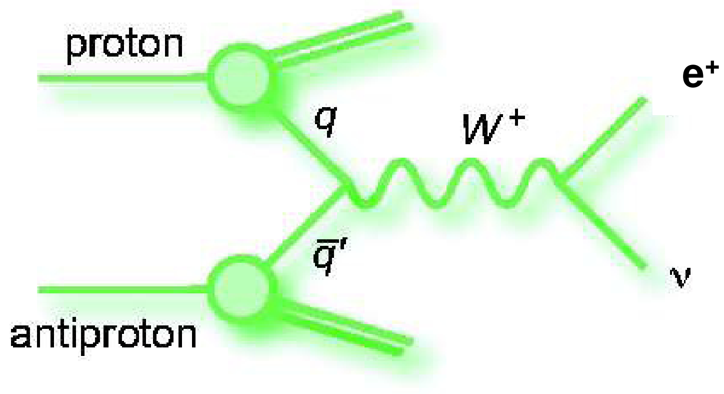


Z->ee in data

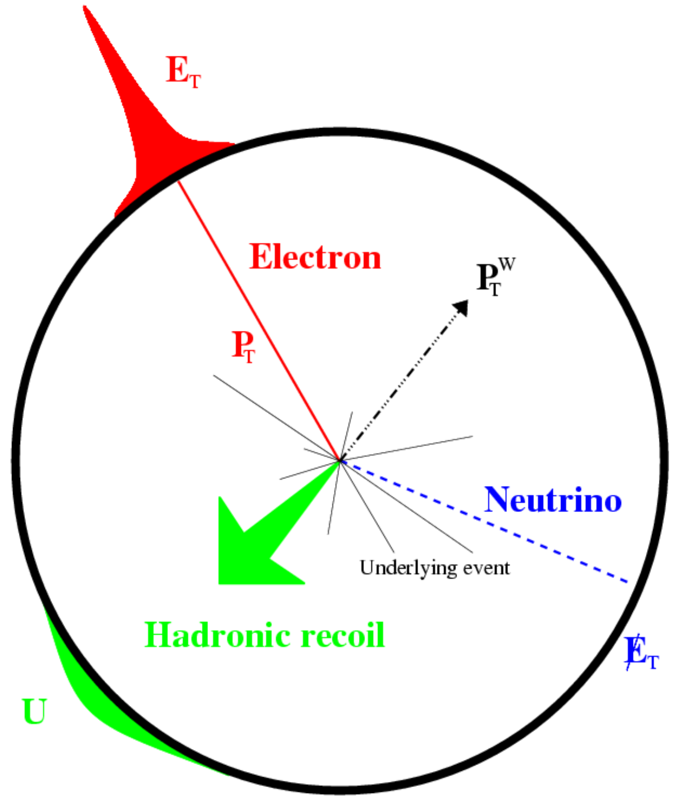


Transverse view

Observables



- We can't detect the W.
- We can't detect the ν.
- We can't detect the longitudinal momentum.
- **We can detect the electron p_T.**

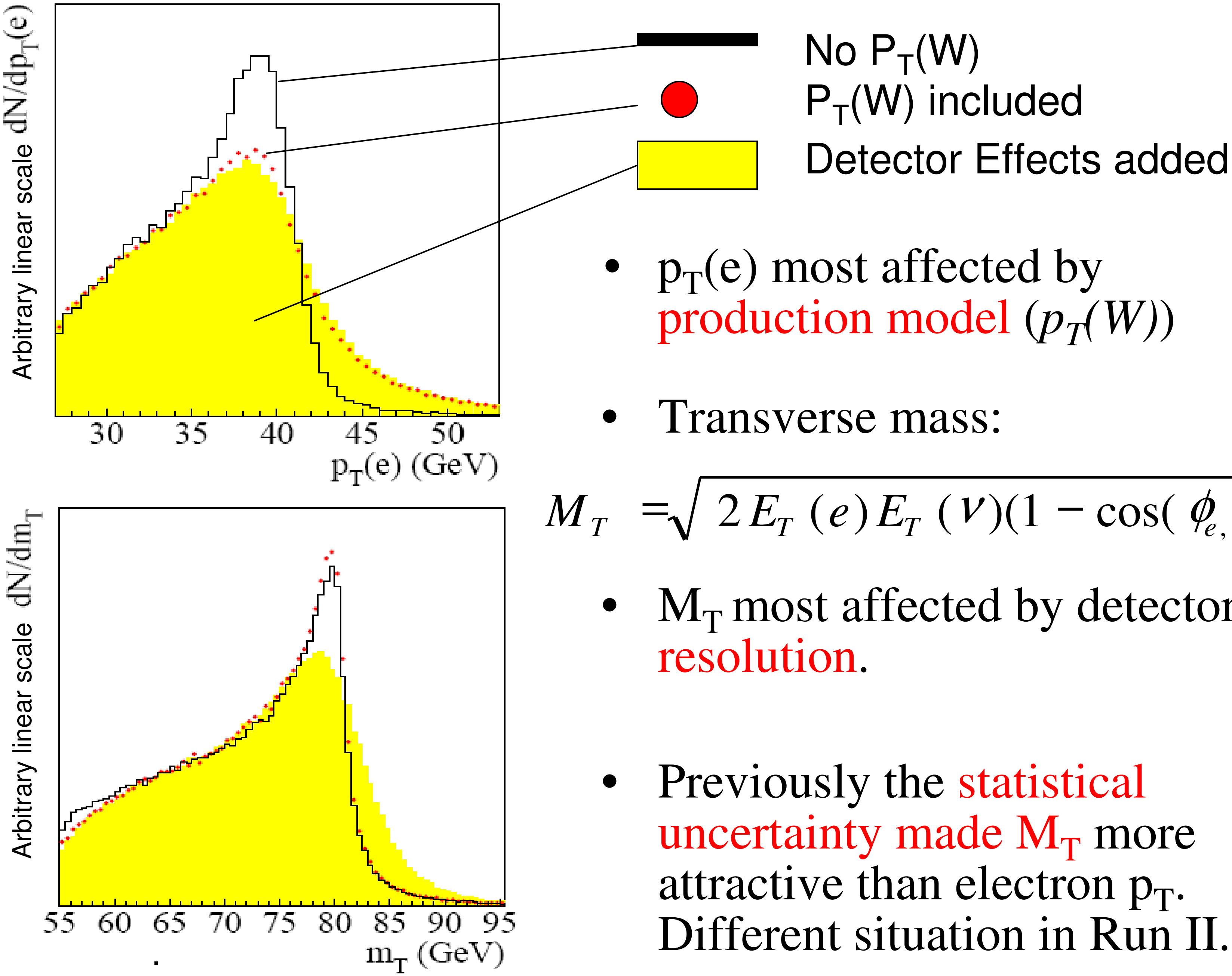


$$\vec{p}_T(w) = \vec{p}_T(e) + \vec{\not p}_T$$

$$\vec{p}_T(\nu) = -\vec{p}_T(e) - \vec{u}_T$$

$\vec{\not p}_T = \vec{\not E}_T$ = MET
frequently used interchangeably

Distributions



- p_T(e) most affected by production model ($p_T(W)$)
- Transverse mass:

$$M_T = \sqrt{2E_T(e)E_T(\nu)(1-\cos(\phi_{e,\nu}))}$$

- M_T most affected by detector resolution.
- Previously the statistical uncertainty made M_T more attractive than electron p_T. Different situation in Run II.

Abbott et. al. (D0 Collaboration), PRD 58, 092003 (1998))

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Outline

Analysis Strategy

1. Calibrate detector:

   Use Z->ee as a standard candle for calorimeter calibration. Advantages: well measured elsewhere, can reconstruct invariant mass at D0.

2. Tune parameterized detector simulation to Z->ee.

   We have 2 separate tunings:

   1. The parameters from the tune to data (the “real” parameters)
   2. The parameters from the tune to full detector simulation Monte Carlo:

      The full detector simulation tuning allows us to develop and test the tools we use with the data and demonstrate we understand the tuning methods.

3. Check tuned detector simulation distributions for Z and W bosons to distributions in full detector simulation and fit for mass (using a templates method).
4. Measure detector efficiencies and backgrounds in data, and apply in the parameterized detector simulation.
5. Check tuned detector simulation distributions and fit M_W using W Electron p_T and M_T distributions in data.

Analysis Strategy -II

Analysis is a blind analysis, and we first test our techniques using Geant full detector simulation monte carlo:

- In this talk I will describe the methods used for calibration and tuning, but I will show only the tuned distributions for the full detector simulation MC.
  - In final tuning (in progress) we do this both full MC and data tuning in parallel.

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   - Monte Carlo and Signal Generation
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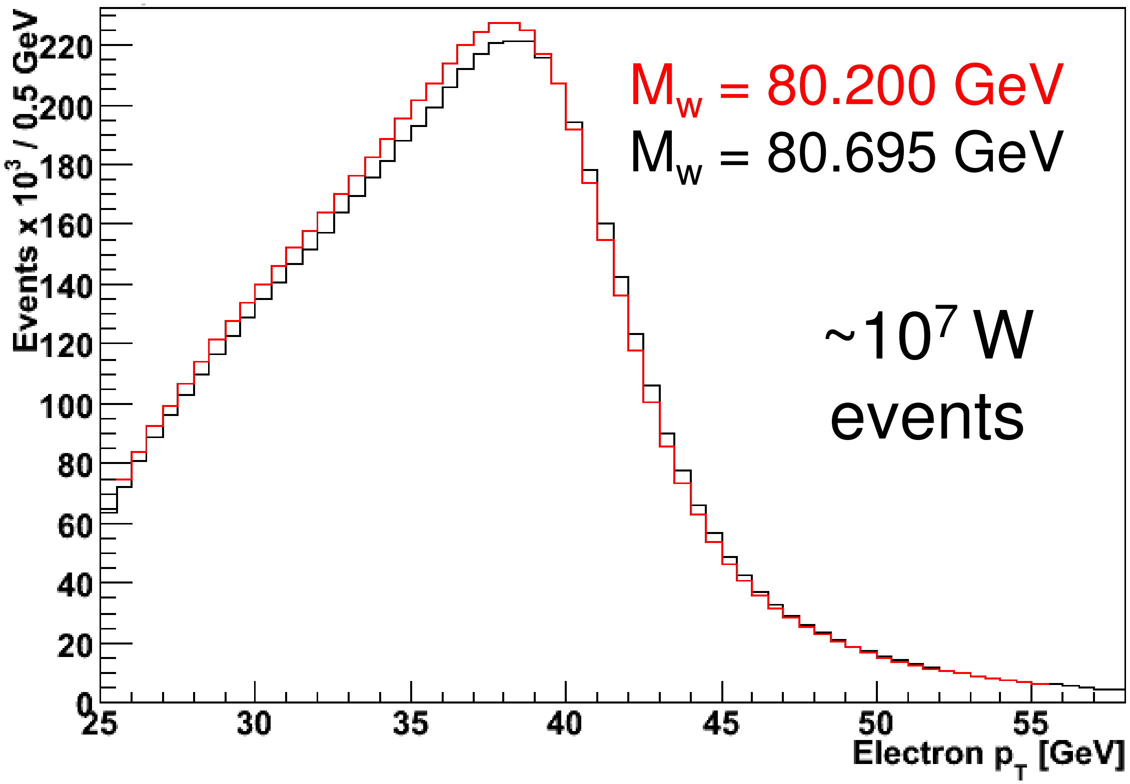
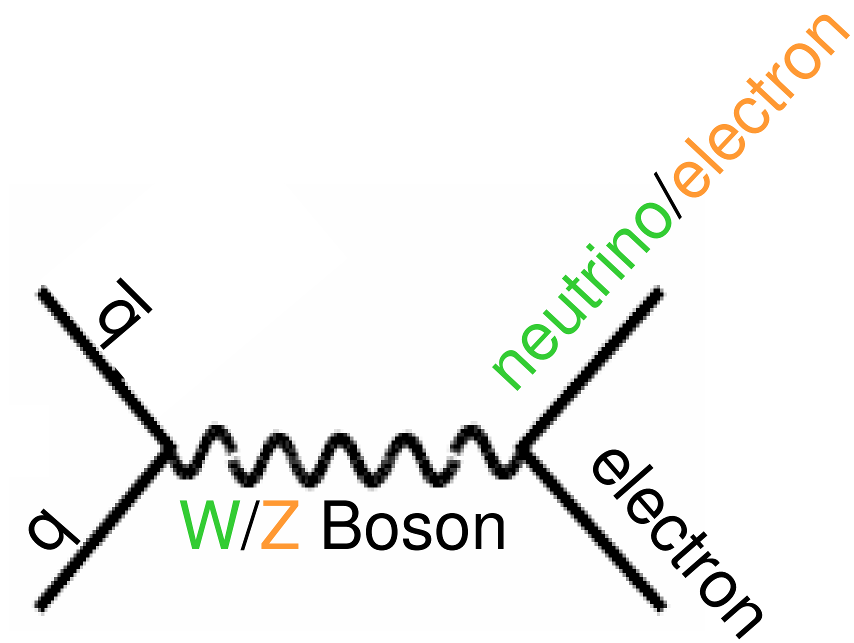
Signal Simulation

- Our signal cannot be described analytically, therefore parameterized Monte Carlo is used to simulate our signal distributions.
- Many high statistics templates generated for the M_T and $p_T(e)$ distributions over a range of M_w.
- Mass determined by fitting to the data using binned negative log likelihood method.



Monte Carlo Signal Generation

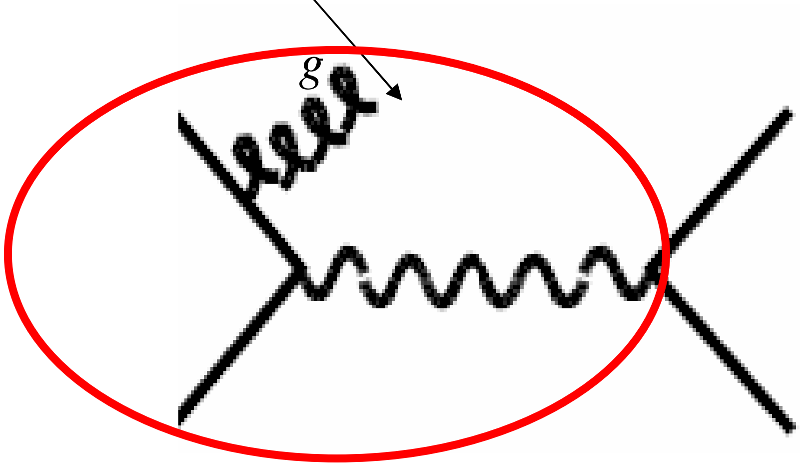
- We use RESBOS (1) + PHOTOS (2) to generate events for our parameterized monte carlo.



1. **C.Balazs, C.-P. Yuan, PRD56, 5558 (1997)**
2. **E. Barberio, Z.Was Comput.Phys.Com.79:291 (1994)**

Monte Carlo Signal Generation

- We use RESBOS (1) + PHOTOS (2) to generate events for our parameterized monte carlo.
  - RESBOS = RESummed BOSon Production and Decay
    - Computes the differential cross-section for $p\bar{p}$->B(->*ll*) where B = boson, *l* = electron or neutrino
    - Includes soft-gluon resummed initial state QCD corrections



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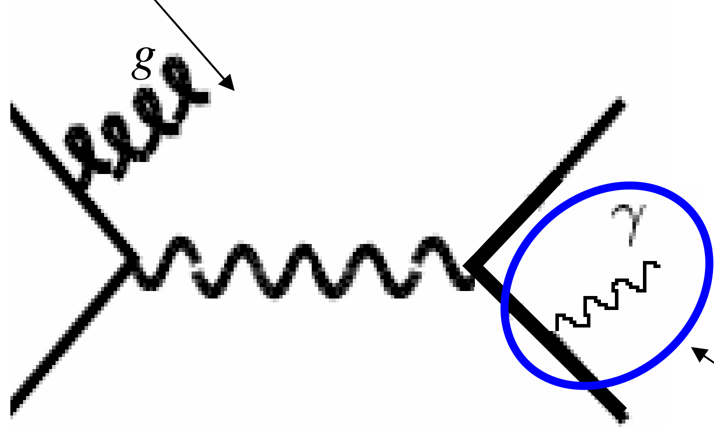

    - PHOTOS simulates QED single photon radiative decays. Used for final state QED radiation.

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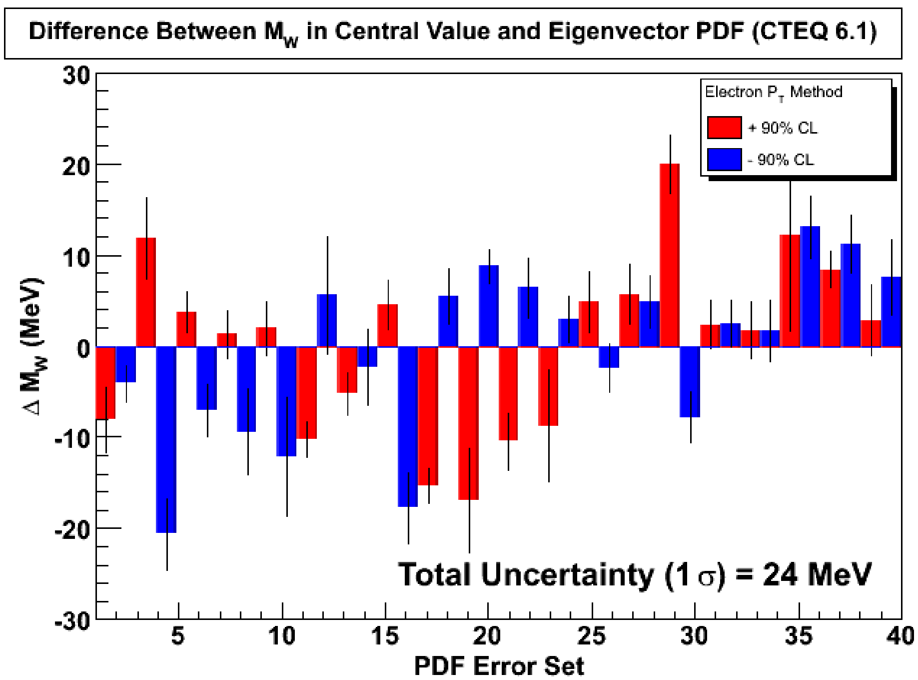
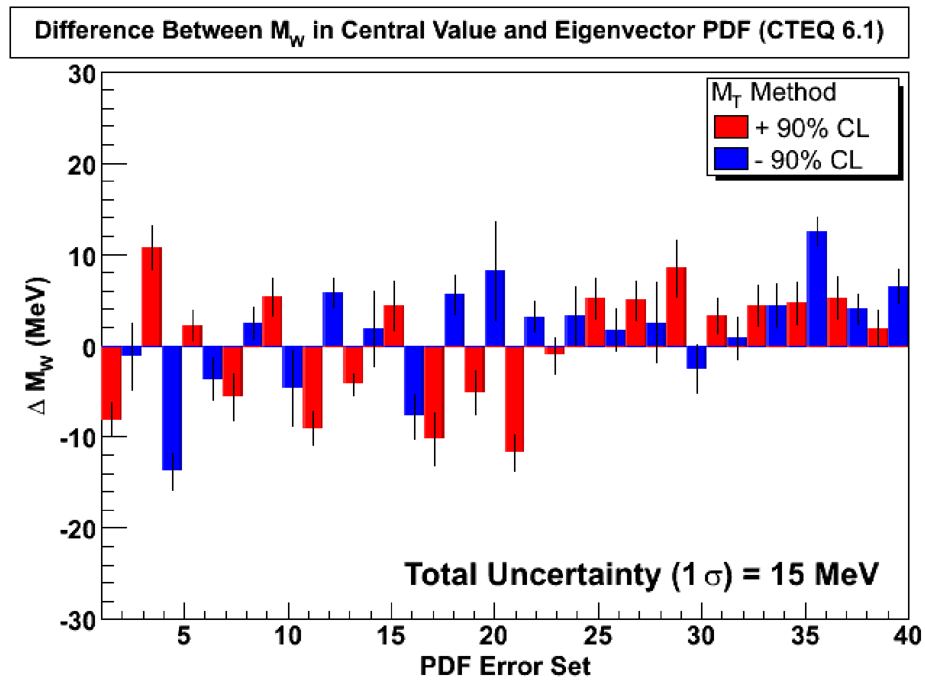
PDF Uncertainty

Parton distributions used as input to RESBOS are derived from global QCD fits to many experiments. We use CTEQ 6.1 parton distribution fits, which have some intrinsic uncertainty.





$$\sigma_{PDF\,\pm} = \frac{1}{1.6}\left(\sum_{i=1}^{n}\left[\Delta M_W\left(S_i^{\pm}\right)\right]^2\right)^{\frac{1}{2}}$$

Conversion to1σ

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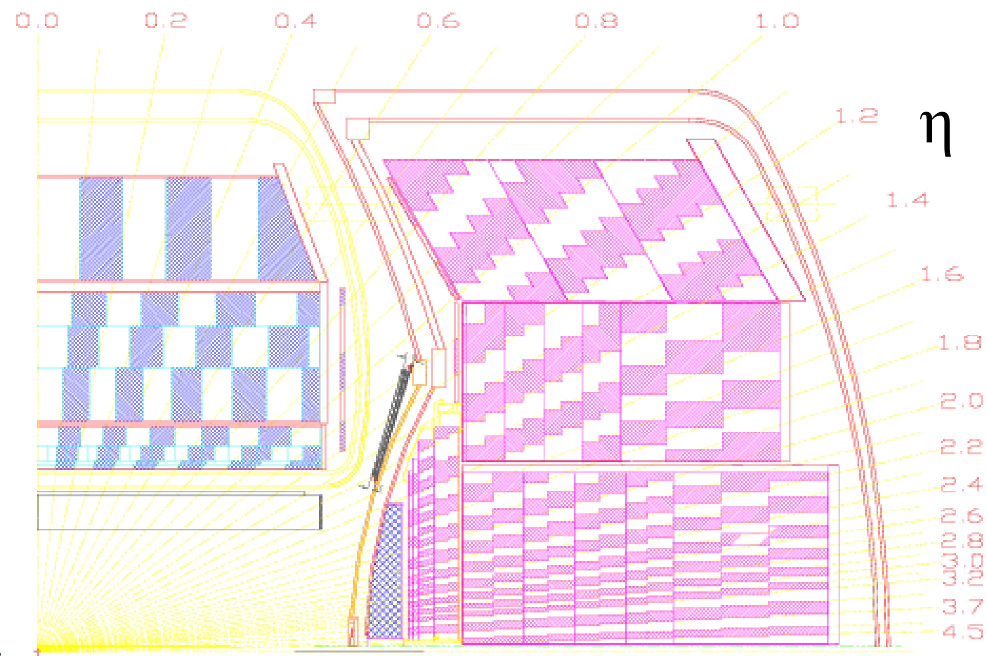
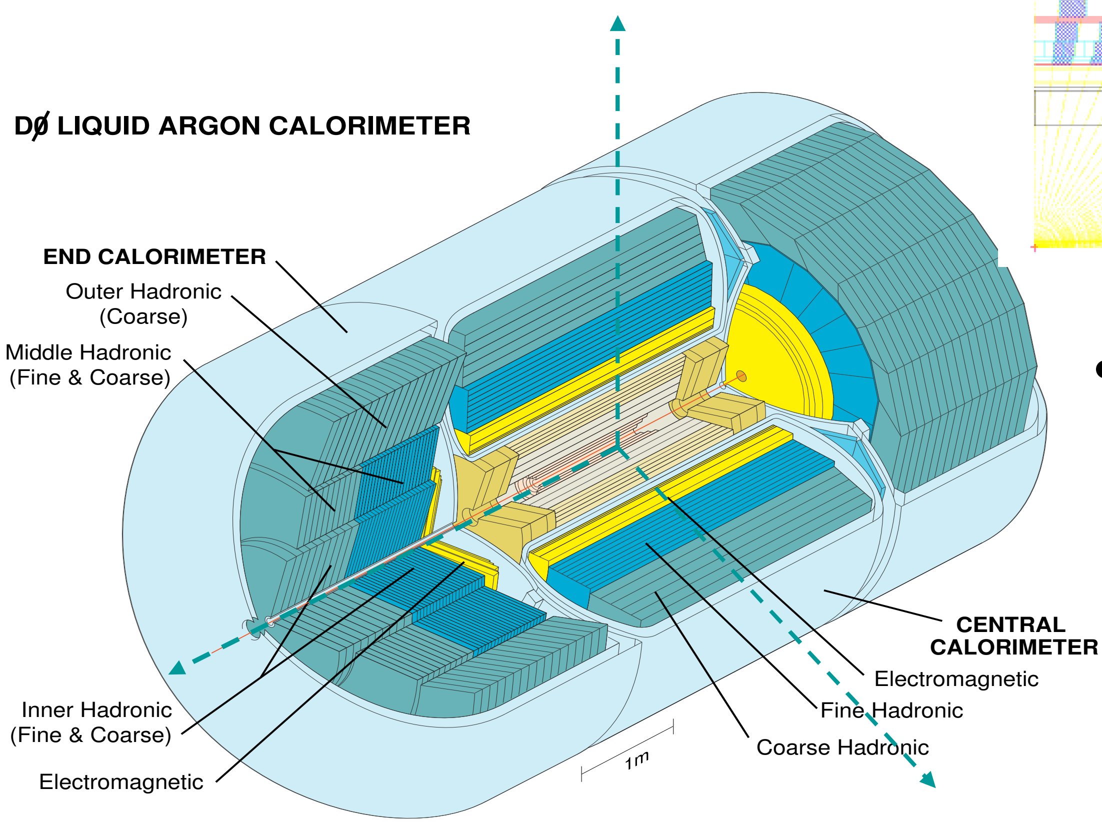
Calorimeter – Electron Energy Measurement

- 3 individual calorimeters: central (CC) and two end caps (EC), all of nearly equal size.
- Liquid Argon Sampling
- Uranium Absorber (Copper, Iron in Course Hadronic layer)

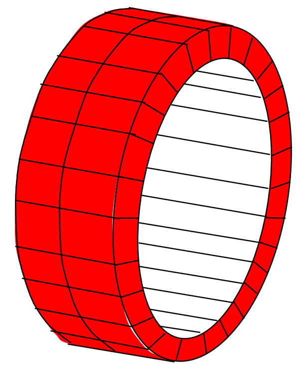




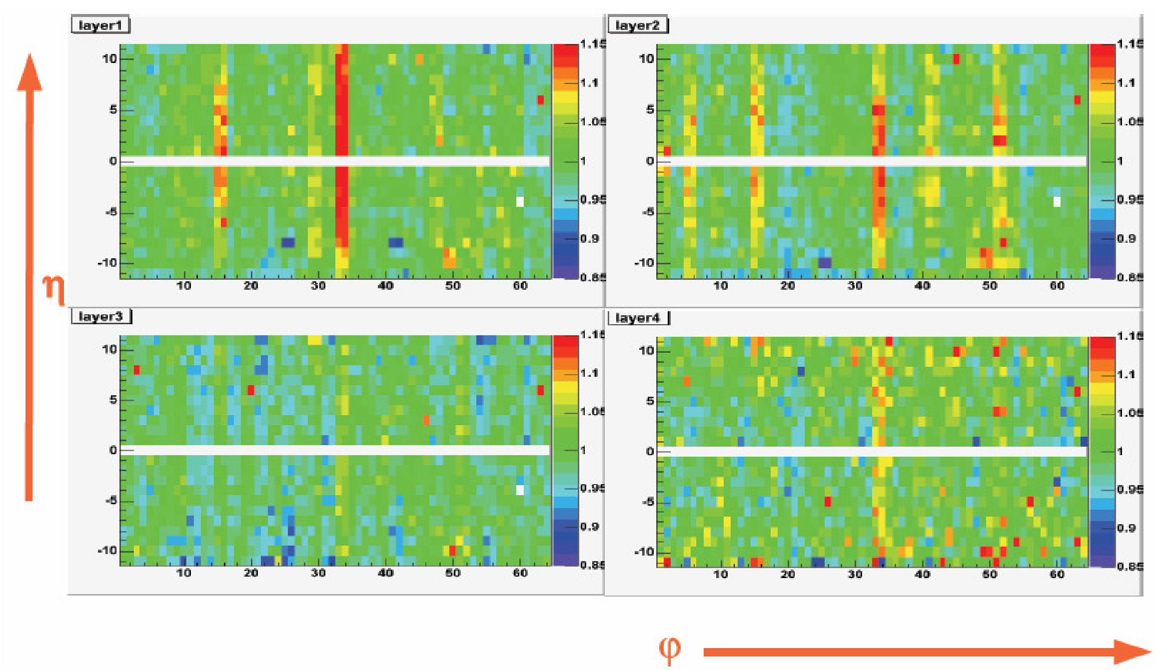
- Electromagnetic (EM)
  - 4 layers, Ur ~ 3mm think
  - 1 cell = 0.1 x 0.1 in η and φ, layer 3 is 0.05 x 0.05.
  - CC EM is 20.5 X_0

Calorimeter calibration

- Online electronics: equalize cell response using pulsers.
- Offline: Determine energy scale from data. First EM calorimeter, then Hadronic calorimeter. Two Steps:
  1. "φ Inter-calibration" Use φ symmetry of detector/physics to make detector response uniform in φ.
  2. "η Inter-calibration" Use Z→ee to set absolute scale in EM calorimeter. (QCD di-jets in hadronic)



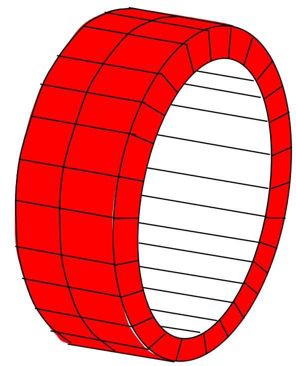
φ inter-calibration:



Data

Calorimeter calibration

2. "η Inter-calibration" Use Z→ee to set absolute scale in EM calorimeter.



With the φ degree of freedom calibrated we have enough Z events to absolutely calibrate each η ring.

Z Mass is: $m = \sqrt{2E_1E_2(1-\cos\theta)}$

E_i are the electron energies and θ is the opening angle from tracking

We find the set of constants $c_{i\eta}$ that minimize the resolution of M_Z and gives the correct (LEP) measured value.

$$E^{raw} = \sum_{(\text{all cells})} c_{ieta} \cdot E'$$

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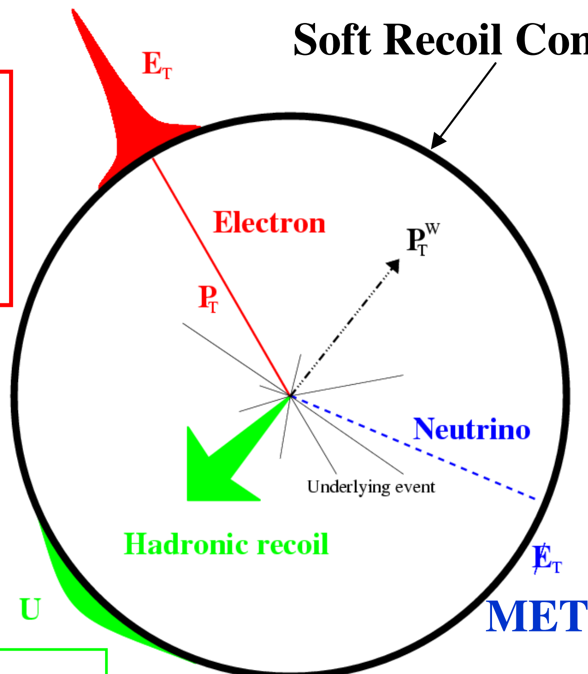
Tuning Detector Simulation

Parameterize electron energy and recoil energy, derive MET.
One parameterization—two tunings: one for data and one for full detector simulation.

Electron

- **Real Electron Energy**
- **Radiated Photons**

Soft Recoil Component



Hard Recoil Component

Recoil System

Every thing but the electron(s)

- **Soft Component: multiple interactions, other parton-parton interactions, electronic noise**
- **Hard Component: Recoil from W/Z boson.**

$MET = -p_T(\text{Electron}) - p_T(\text{Recoil})$

Event Selection

- Selection determined to reduce backgrounds and focus on a well modeled region of the detector:
  - Electron:
    - p_T>25 GeV,
    - matched track > 10 GeV
    - Central Calorimeter
    - Isolated
    - Electron like shower shape (Hmatrix)
  - W Boson
    - W p_T<30 GeV
    - $p_T(\nu)$>25 GeV
  - Z Boson
    - Z p_T<30 GeV with 2 electrons

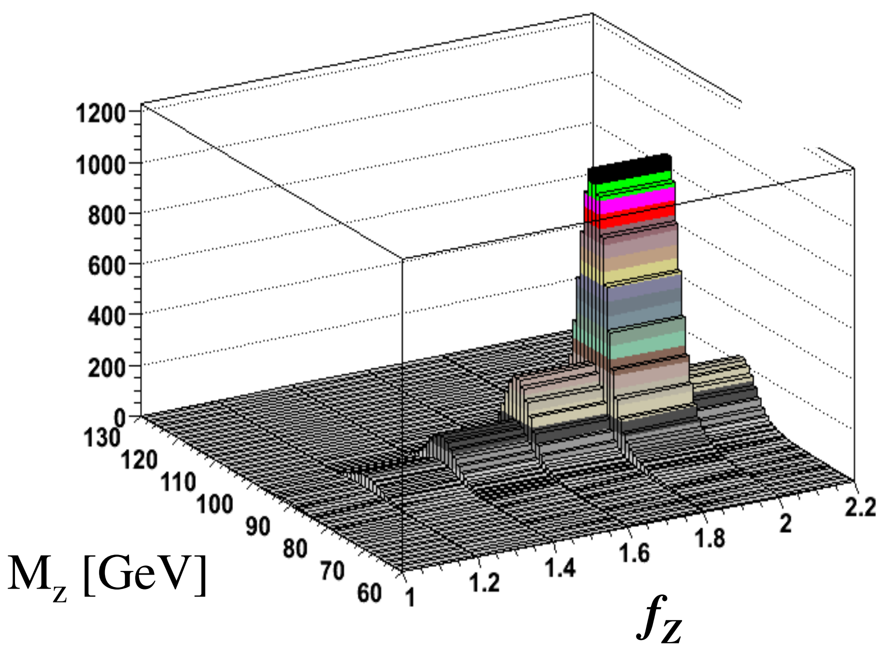
Electron Energy Tuning

The electron energy scale is the dominant systematic uncertainty. We model the electron energy response in parameterized MC as a linear function of scale (α) and offset (β):

$$E_{measured} = \alpha \times E_{true} + \beta$$

The kinematic variable f_Z gives us the most information about the parameters:

$$f_Z = \frac{\left(E(e_1) + E(e_2)\right)\left(1 - \cos(\gamma_{ee})\right)}{m_{measured}}$$



The mass can be written in terms of the scale and offset.

$$m(ee) = \alpha \cdot m_Z(LEP) + \beta \cdot f_Z$$

$$\frac{\partial m(ee)}{\partial \beta} = f_Z$$

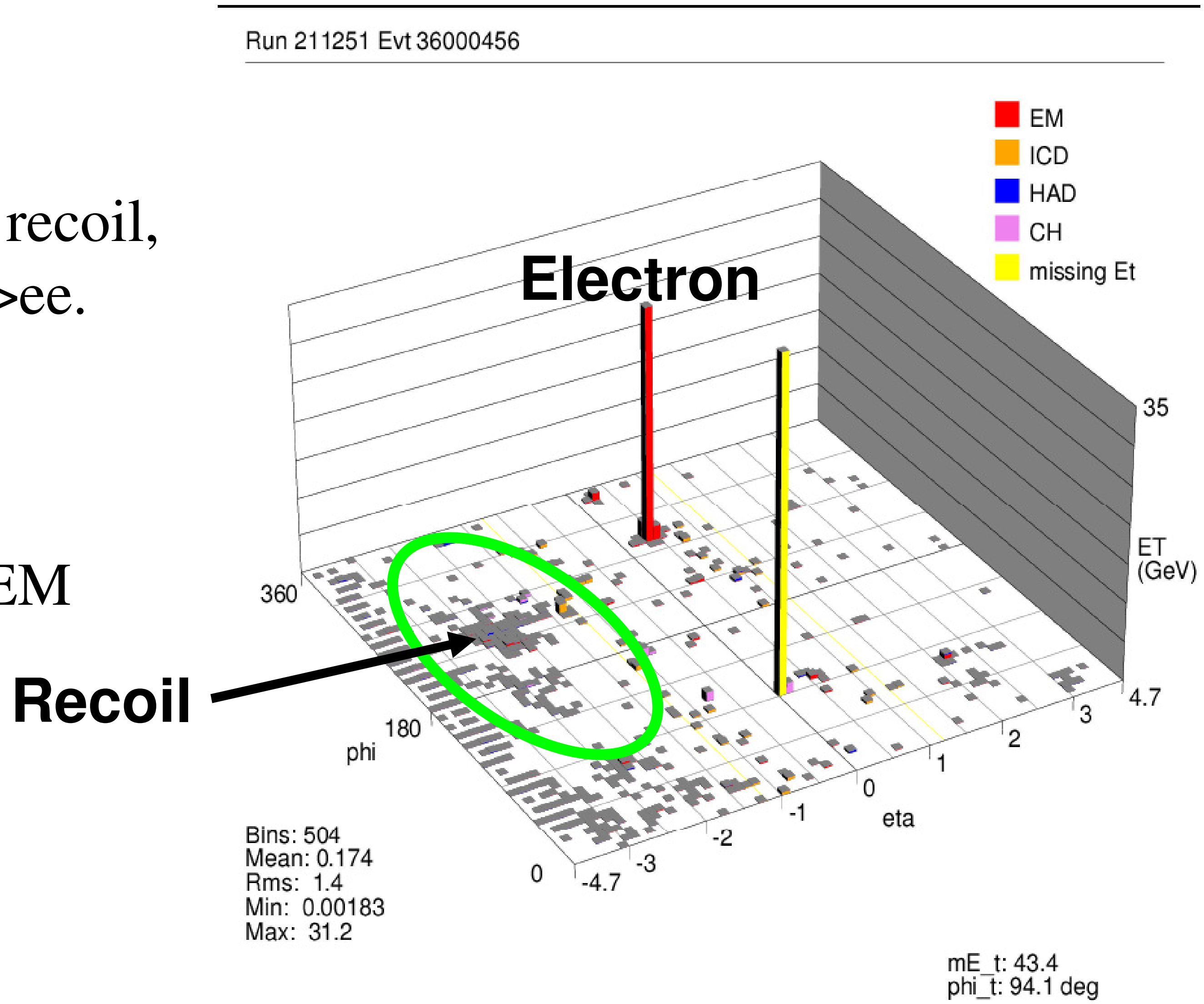
Results in ΔM_W of 13 MeV

Hadronic Recoil Tuning

- The hadronic recoil is the energy of all the other particles in the event except the decay products of the boson.

- Z and W have similar recoil, again we tune using Z->ee.

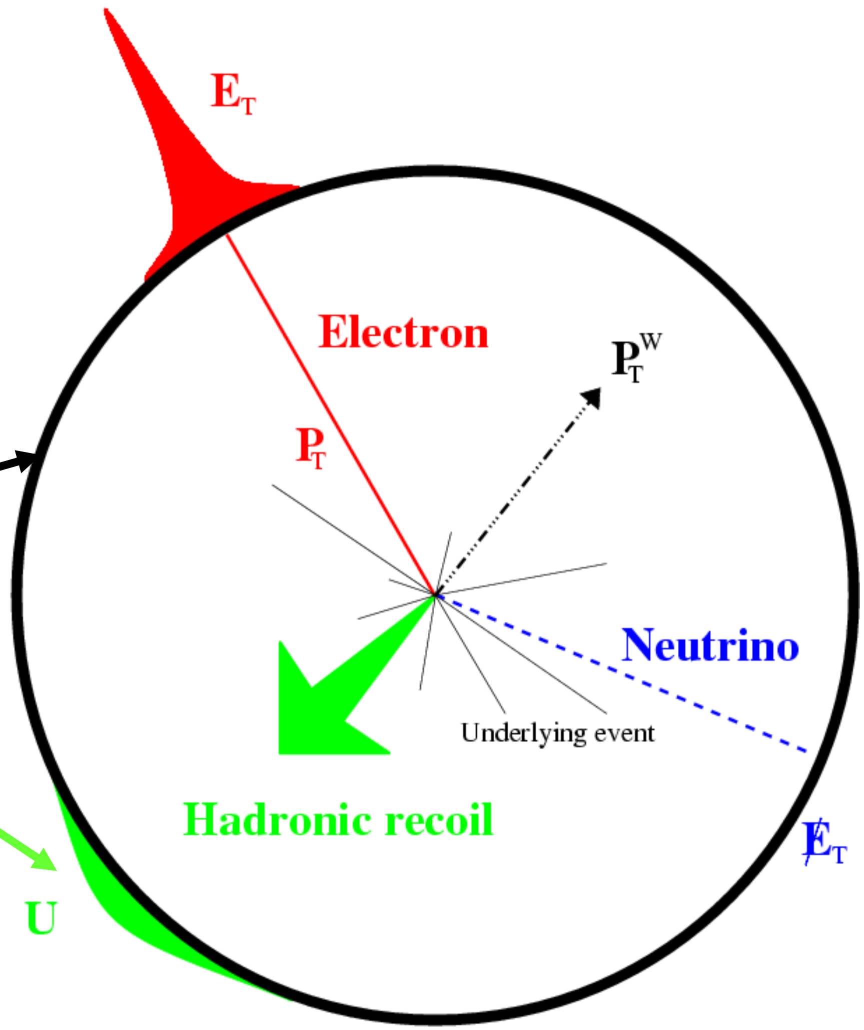
- Z->ee and balance the hadronic recoil p_T with calibrated electrons in EM calorimeter.



Hadronic Recoil Calibration

• The hadronic recoil is the energy of all the other particles in the event except the decay products of the boson.

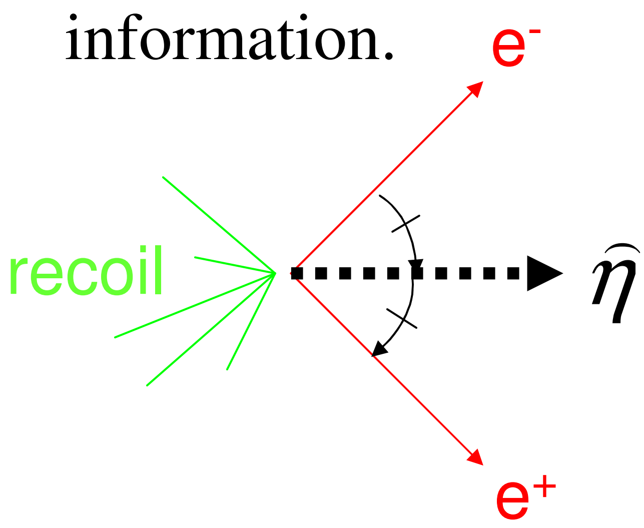
- There are two contributions to the hadronic recoil:
  1. A "soft," isotropic contribution from additional interactions--described by a library of low bias events.
  2. A "hard," jet-like contribution in the direction opposite the boson.



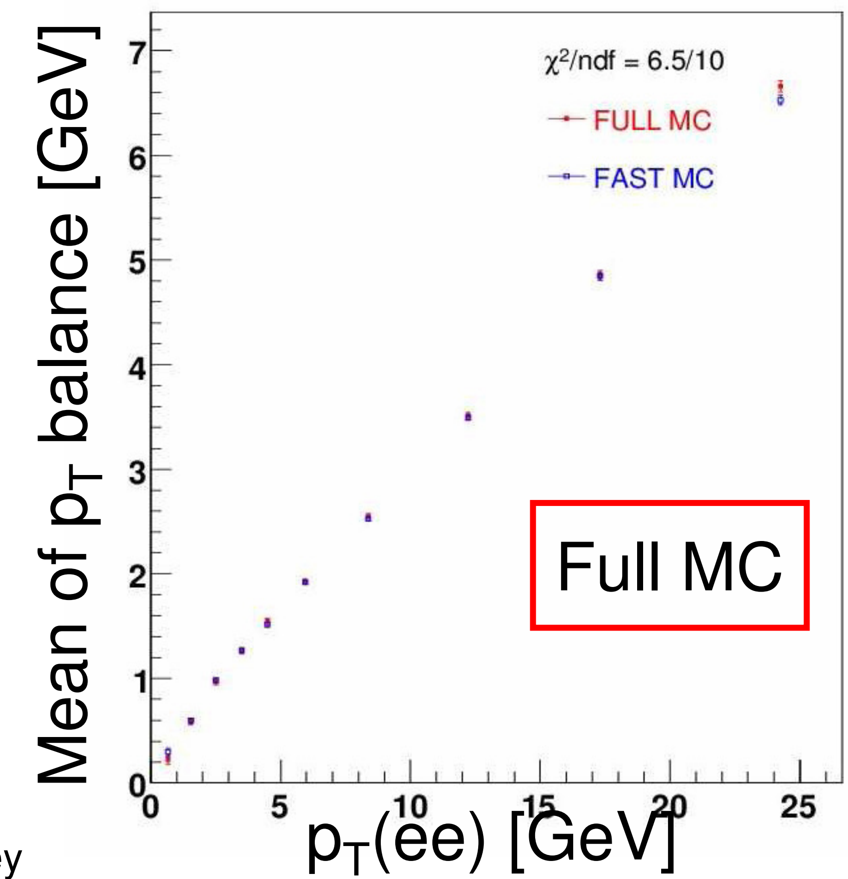
Hadronic tuning with Z→ee events

- We tune the monte carlo parameters for the "soft" and "hard" components together in the using Z→ee events.

- The distribution of $p_T(ee) + p_T(\text{recoil})$ along η axis gives us the best information.



Minimizing the chi^2 between the data or full monte carlo and the parameterized monte carlo gives us the hadronic recoil parameters.



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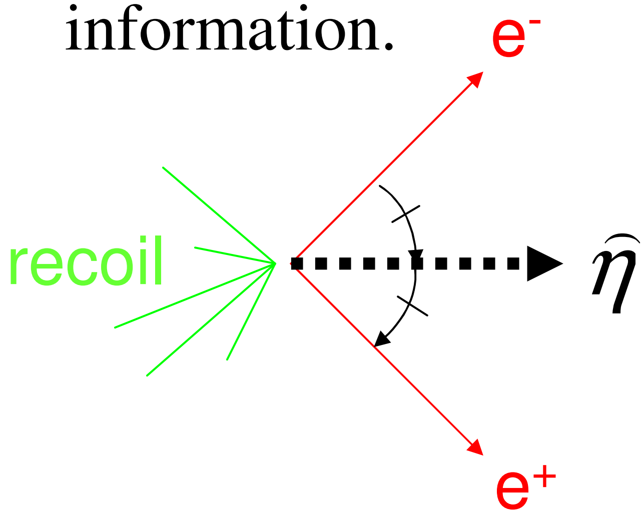

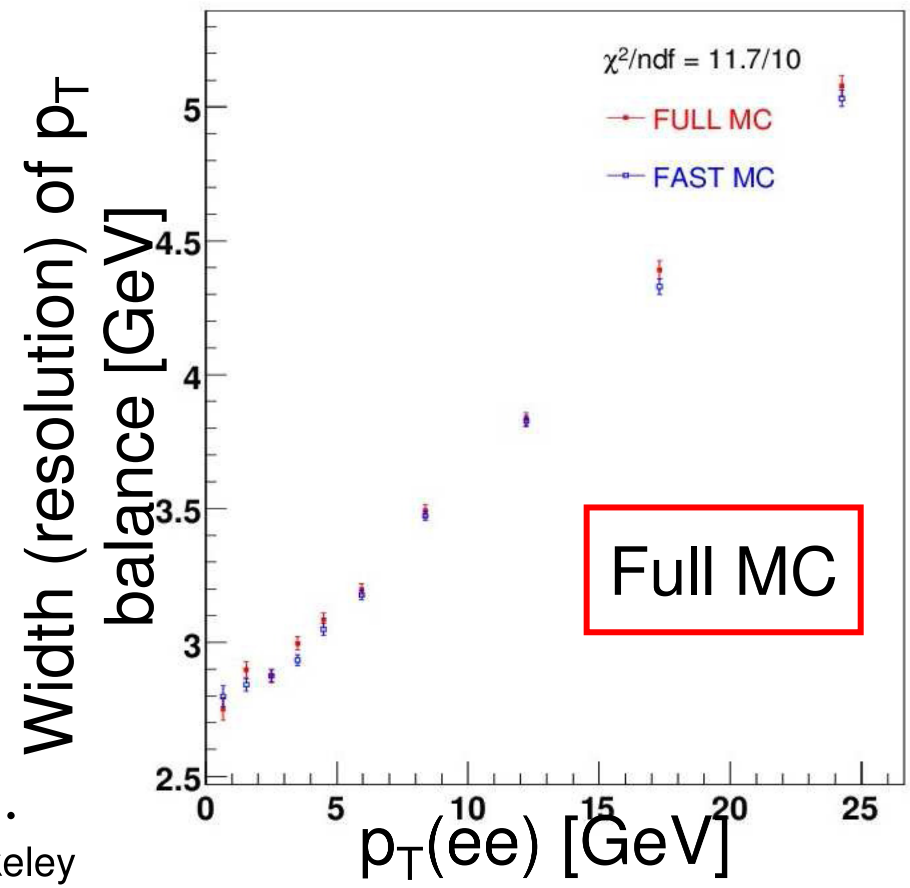

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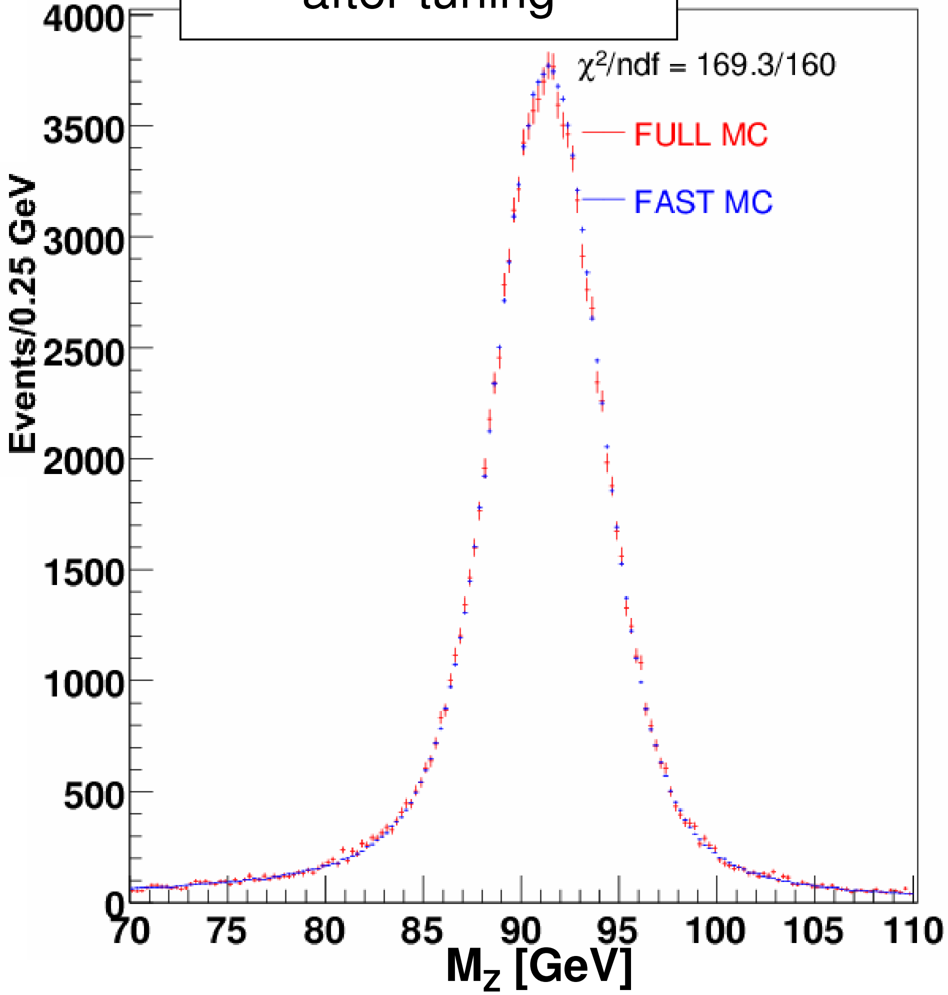
Results of Tuning

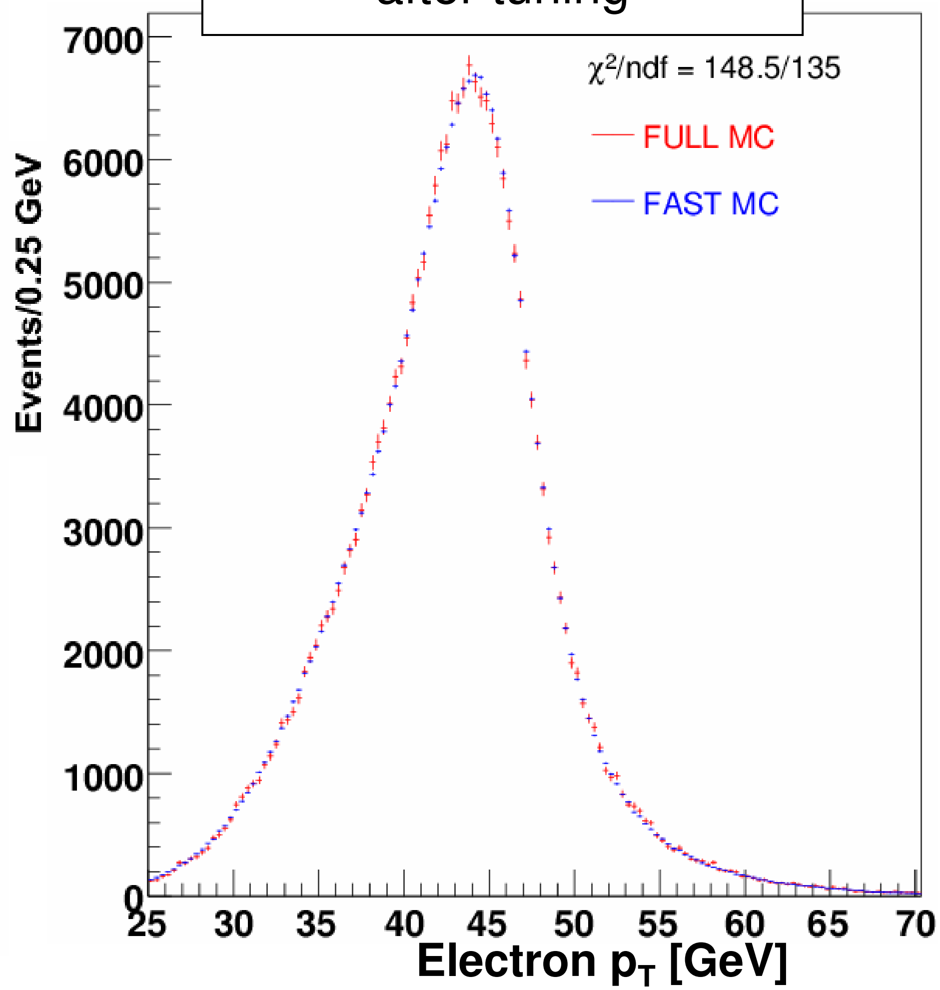
Full MC

The Z boson mass and electron p_T distributions indicated that we have calibrated the calorimeter and parameterized the response well.

Z Mass comparison after tuning



Electron p_T Comparison after tuning

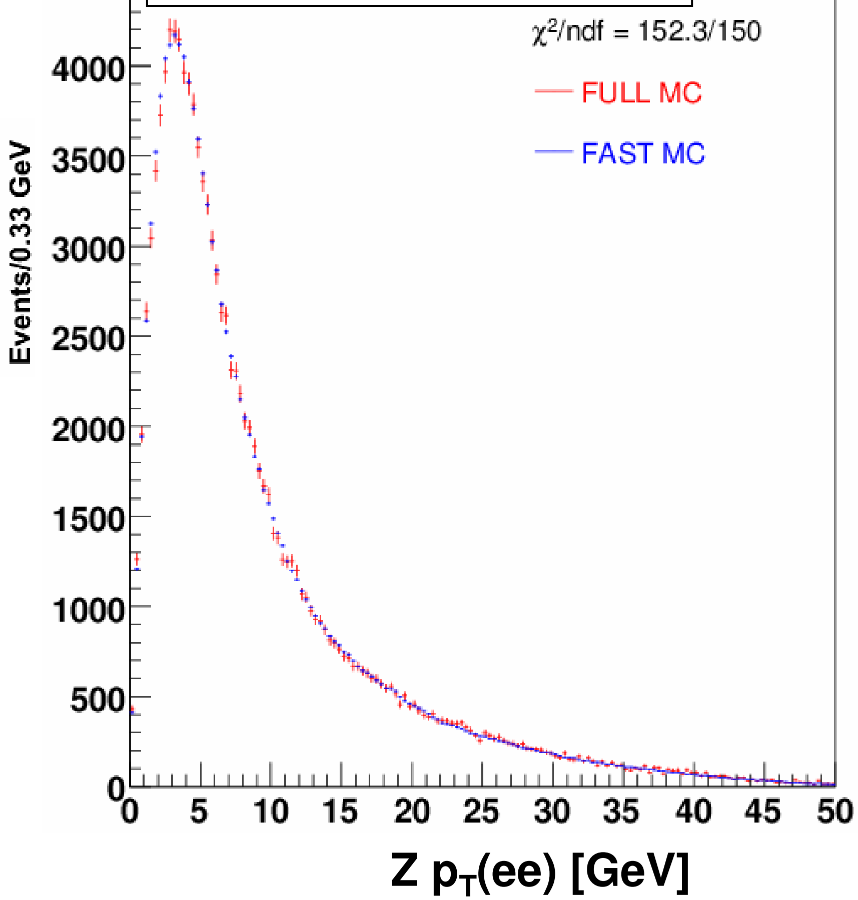


Hadronic Model

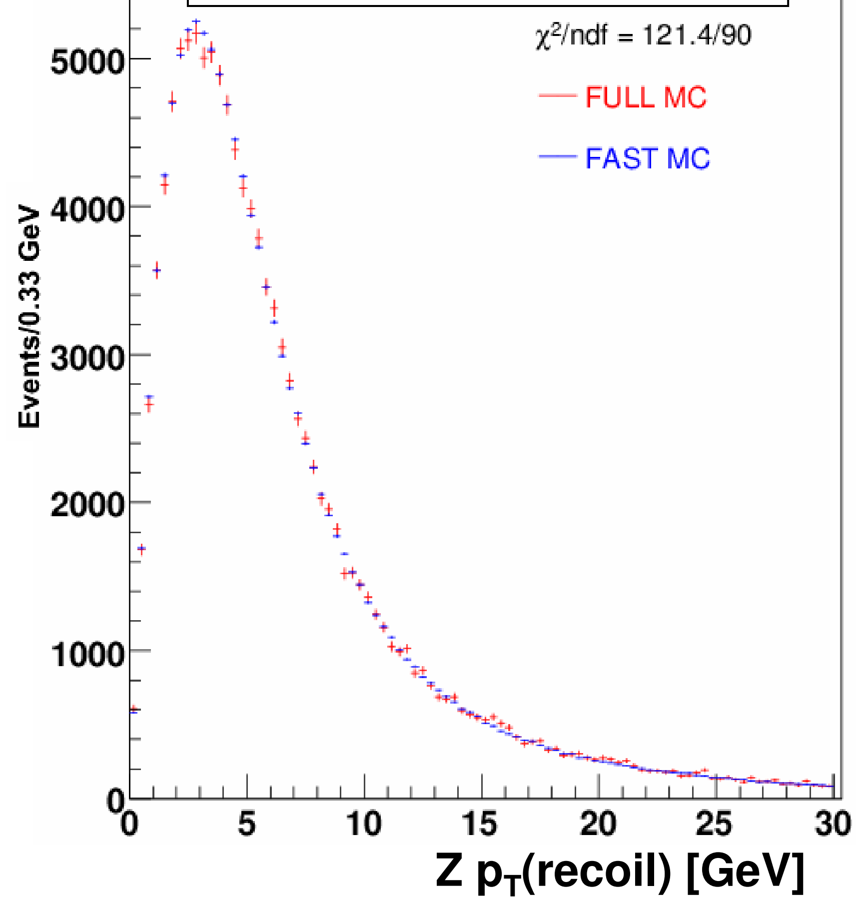
Full MC

Z boson p_T spectrum from Pythia/Geant monte carlo and parameterized monte carlo show good agreement:

Z p_T(ee) comparison after tuning

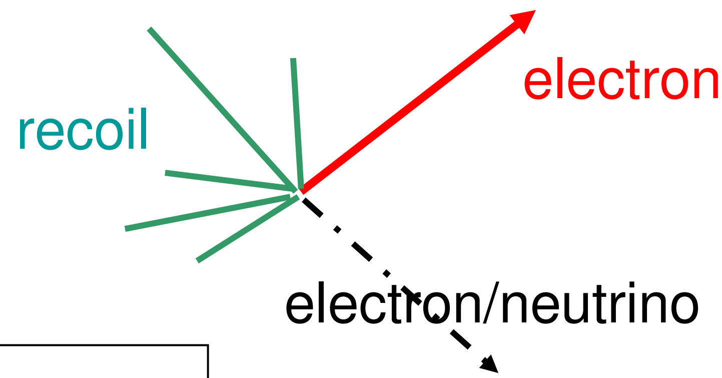


Z p_T(recoil) Comparison after tuning

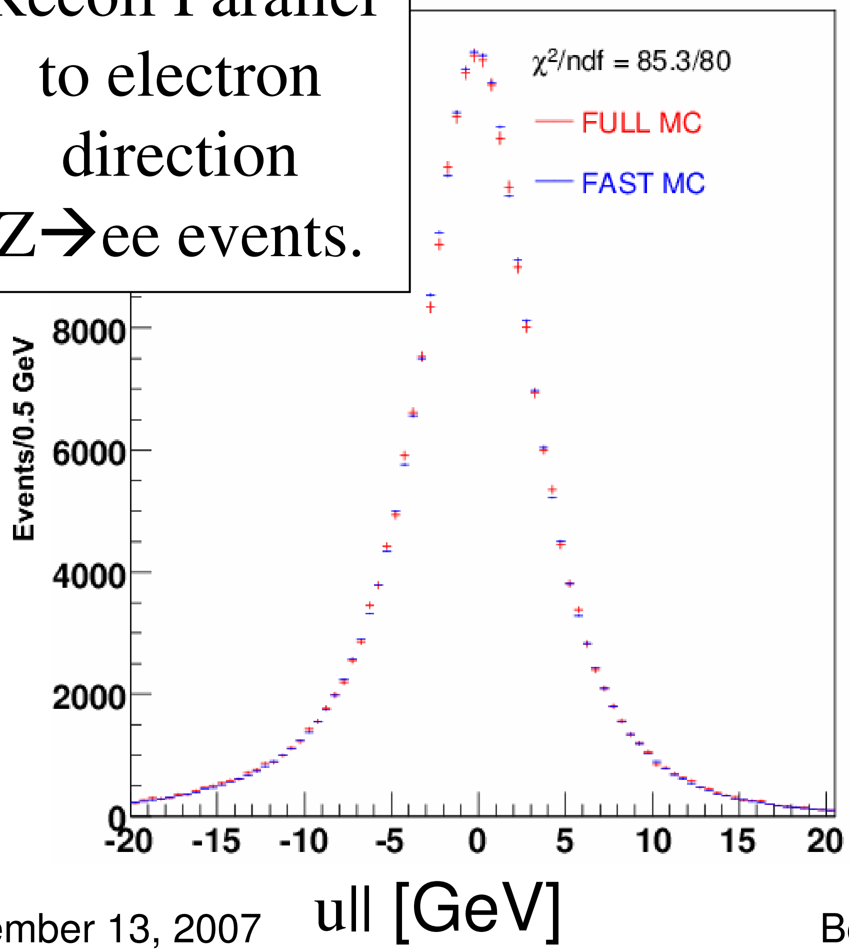


Hadronic Model

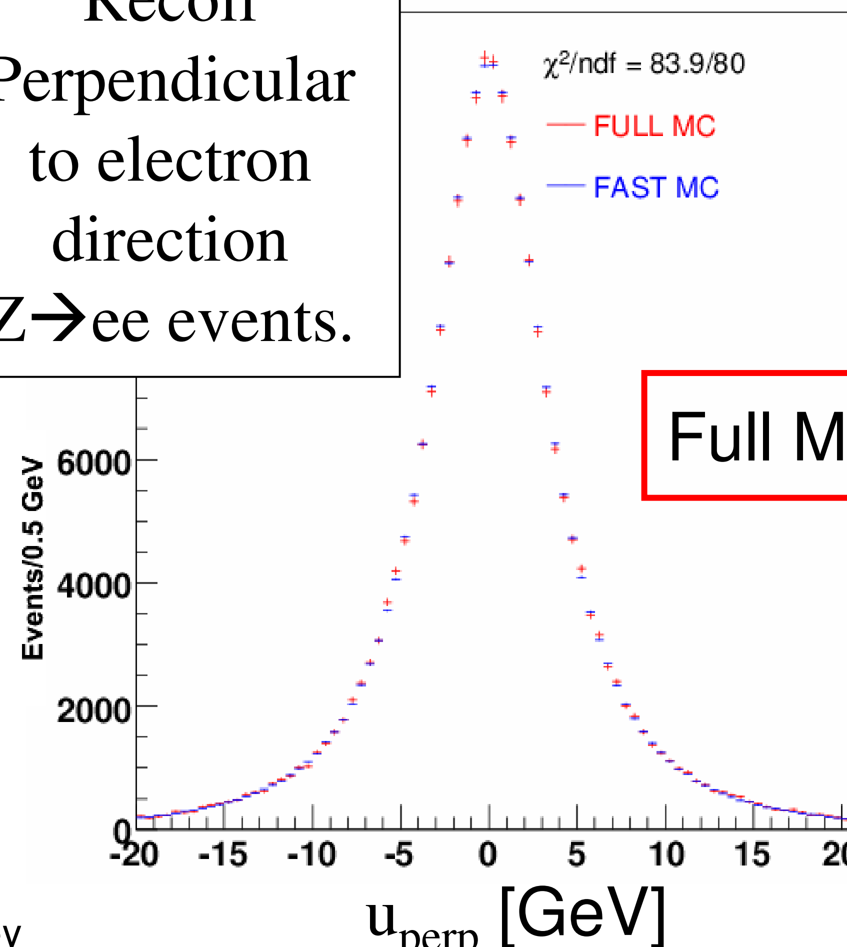
Recoil parallel to the electron affects mass measurement directly and is an important check of the model.



Recoil Parallel to electron direction Z→ee events.



Recoil Perpendicular to electron direction Z→ee events.

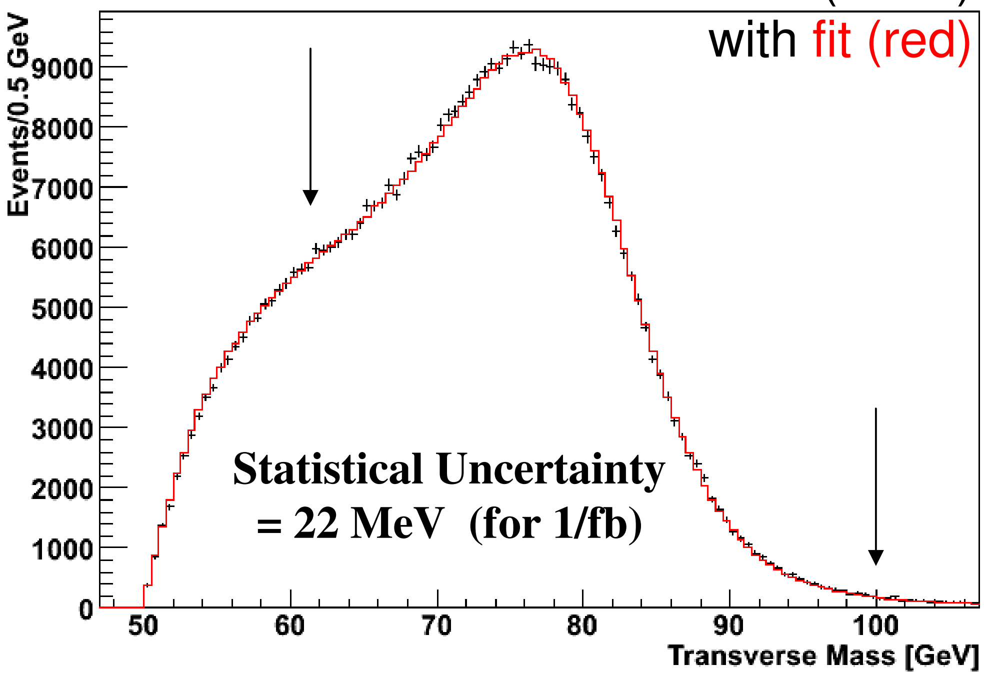


Full MC

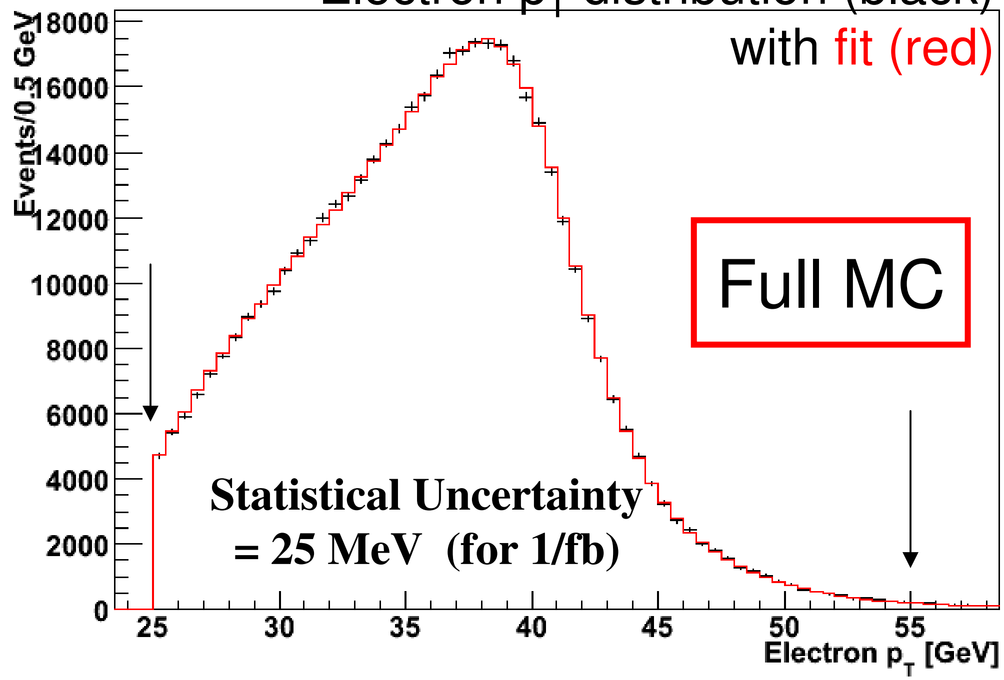
Mass Fit

M_W fit done treating full MC as data.

Transverse mass distribution (black) with fit (red)



Electron p_T distribution (black) with fit (red)



$\downarrow$ = Fit range Transverse mass: [60,100] GeV, electron pT: [25,55] GeV

Results consistent with "true" value within uncertainty.

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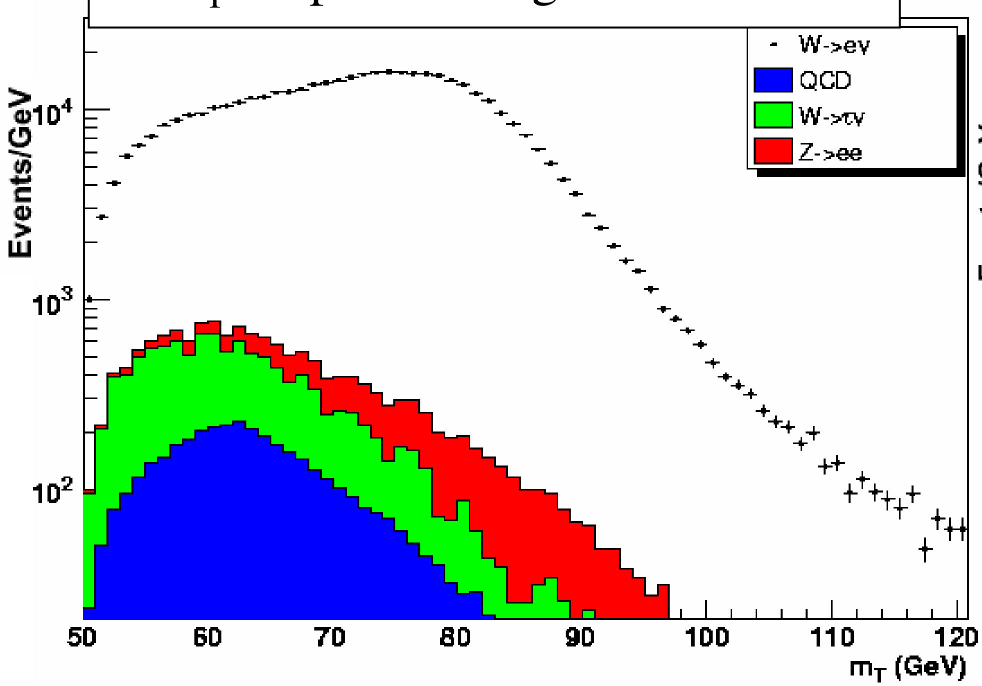
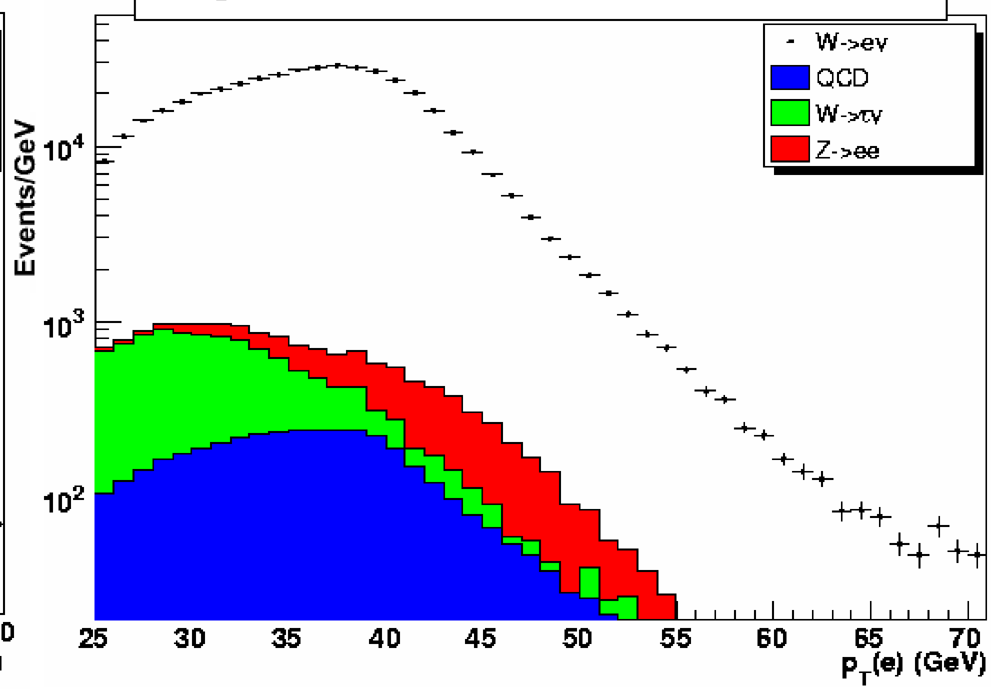
Backgrounds

The background contributions to M_T and $p_T(e)$ distributions are small. Studied using Pythia/Geant monte carlo (W->$\tau\nu$, Z->ee) and data (QCD):

M_T shape of background events



p_T(e) shape of background events



---: QCD =1.0%

---: W->τν->eννν = 1.7%

---: Z->ee =1.1%

Outline

1. Motivation
2. Overview of Method and Detector
3. Strategy for the Measurement
4. Details of the Analysis
5. Systematic Uncertainties
6. Prospects and Conclusion

Blind analysis

Analysis is blinded by a random offset [-2.0 GeV, +2.0 GeV] in our $W \rightarrow e\nu$ comparisons and likelihood fitting.

When analysis is frozen we will unblind.

Uncertainty estimates

Preliminary uncertainties for 1/fb data sample:

Source	M_t ΔM_W [MeV]	Electron P_t ΔM_W [MeV]	Run I ΔM_W [MeV]
W stat	22	25	60
Electron Energy Response	7	11	56
Electron Energy Linearity	7	6	|
Electron Energy Resolution	2	2	19
Hadronic Response	24	16	37
Hadronic Resolution	10	5	|
$u_{\|\|}$	5	15	|
Background	4	6	9
PDF	15	24	8
$P_t W$	2	5	10
QED	7	9	15
W Width	10	10	10

- Analysis of data is in progress.
- Parameter values may change, but parameter uncertainties relatively stable.

Prospects

What we have done:

- EM Calorimeter well understood.
- Recoil measurement well understood.
- Theoretical and systematic uncertainties understood.
- Measurement technique applied developed and successfully tested with full detector simulation.

Blind analysis with data in progress.

Exciting times: 1/fb result for Winter '08.

Longer term: Full Tevatron Run II measurement will be a legacy that may stand for some time.